OCT 30 1959

NASA TN D-58

NASA TN D-58

C1

7N-08
199061
39P

TECHNICAL NOTE
D-58

THE EFFECTS OF VARIOUS COMBINATIONS OF DAMPING AND CONTROL POWER ON HELICOPTER HANDLING QUALITIES DURING BOTH INSTRUMENT AND VISUAL FLIGHT

By Seymour Salmirs and Robert J. Tapscott

Langley Research Center
Langley Field, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON October 1959

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL NOTE D-58

THE EFFECTS OF VARIOUS COMBINATIONS OF DAMPING AND CONTROL POWER ON HELICOPTER HANDLING QUALITIES DURING BOTH INSTRUMENT AND VISUAL FLIGHT

By Seymour Salmirs and Robert J. Tapscott

SUMMARY

A helicopter flight investigation has been conducted by means of visual flight maneuvers and Instrument Landing System (ILS) approaches conducted under simulated blind-flying conditions to permit detection of the effects of control power and damping variations on handling qualities.

The results showed that the handling qualities are improved as the damping is increased (at least in the range of damping covered during the investigation), but that changes in handling qualities are less directly dependent on variations in control power. Satisfactory control powers were found to cover a range with a minimum slightly greater than that originally available in the helicopter and a maximum of about three times the original value. Increasing the damping increased the range of desirable control powers. Summary charts are presented which show the effects of control power and damping on the handling qualities. These charts are expected to be useful in estimating desirable characteristics for other helicopters and VTOL types of aircraft and are based on the results of this and previous investigations.

Pilots controlling the cyclic stick with their fingers (as opposed to holding the stick firmly with the hand) achieved better results and found higher control powers more desirable. The cyclic stick force gradient had little effect on the results as long as some appreciable gradient was present.

INTRODUCTION

Helicopter instrument flights have indicated a need for improved handling qualities. The results of references 1 and 2 in particular have shown that large improvements in handling qualities may be realized from increases in damping (moment due to angular velocity) while the control power (moment per unit control deflection) was kept at a constant value.

The present paper deals with more recent tests in which the control power was varied in conjunction with the damping variation in an effort to supply some information on the effects of control power as well as determine any interdependence of damping and control power.

In addition, both control power and damping were reduced to very low values to extend the range investigated and to examine the handling-qualities effect of low damping values such as could result from high-speed high-performance helicopter designs as predicted by reference 3. An extrapolation of the results of references 1 and 2 would indicate that low damping may very seriously affect the handling qualities since the helicopter with its inherent damping was considered to be marginal. Since low control power is usually considered detrimental by pilots, the investigation included a determination of the degree to which reduction in control power affects the handling qualities.

The changes in stability characteristics during these tests were effected by electronic components because of the broad scope of the investigation and the advantages to the test program of immediate adjustment of characteristics. In an actual design, however, use of airframe design methods such as are outlined in reference 4, either alone or in combination with automatic devices, would be expected to be more desirable than reliance on electronic components as was done during this particular test program.

The results obtained from this investigation were evaluated on the basis of the pilots' opinions of the handling qualities and by a statistical procedure for estimating the effects on handling qualities of the changes made.

DEFINITIONS

control power	moment on helicopter produced for a given control displacement
damping	moment on helicopter proportional to and opposing angular velocity

RESEARCH HELICOPTER

The research helicopter, shown in figure 1, is equipped with electronic components that permit in-flight variations of control power and damping of the helicopter. Descriptions of the helicopter and its electronic components have been given in references 1 and 5 and its physical characteristics are listed in table I. The electronic components were modified slightly in this case to permit a reduction in the apparent damping of the helicopter. In addition, it was possible to vary, electrically, the ratio of control deflection to rotor-blade pitch angle; thus, the pilot was able to vary his "apparent" control power.

In the present investigation the apparent damping of the helicopter was varied from values of about zero to about three times the original damping of the helicopter. The highest values of damping used were the values reached and found desirable in reference 1. In conjunction with the damping variation, the apparent control power was varied from about one-half that built into the helicopter to values about four times the original values. The actual values of this helicopter's original damping and control power as well as the maximum damping increment are given in detail in reference 5. The original control power, in terms of the pilot's control displacement, the original damping, and the control displacements measured at the point of application of control force are presented in table I.

The helicopter was instrumented with standard NASA recording instruments which recorded pilot's control positions, roll, pitch, and yaw velocities, heading, airspeed, and Instrument Landing System (ILS) instrument localizer and glide-slope indications.

FLIGHT PROCEDURES

The initial evaluations were conducted through the use of visual maneuvers including take-off, landing, hovering, quick-stops, and forward flight at various speeds. Instrument patterns were also flown under simulated instrument conditions. Primary emphasis, however, was placed on ILS approaches at low speeds during simulated blind-flying conditions. The maneuver is sufficiently difficult so that any handling-qualities differences become readily apparent through the ease or difficulty of making the approach. The ILS approach applies a fixed standard so that different pilots can perform the same task; thus the possibility of quantitative analysis is enhanced.

On each flight involving the ILS approaches, the first and final approaches were made with the helicopter in the same configuration.

Intermediate approaches were made with variations in damping and/or control power. In some instances one of the intermediate approaches was flown in the same configuration as the first and last approaches. The use of the same configuration in both the first and last approaches permitted the evaluation, insofar as possible, of any effects of pilot learning or fatigue. Normally, each flight was limited to five approaches to eliminate undue pilot fatigue. This limitation also meant that a flight would be completed in a short time; thus, the effects of atmospheric variations between runs are minimized. Approaches of each flight are therefore comparable whereas successive flights may not be directly comparable.

The range of the investigation is briefly illustrated in the following table:

Control power	Damping			
	Very low	1/2 original	Original	High
1/2 original		X	X	X
Original	X	X	X	X
Twice the original		X	X	X
Four times the original		X	X	X
Various powers		X	X	X

ANALYSIS OF FLIGHTS

The results of the investigation were evaluated by pilots' opinions of the handling qualities and by a statistical analysis of the records. The pilots' opinions were used exclusively during the visual flight maneuvers and while flying instrument flight patterns. On later flights involving ILS approaches, both the opinions of the pilots and statistical methods were used. A total of 35 visual and instrument flights were flown of which 19 were found suitable for the statistical analysis.

Pilots' Opinions

The pilots' opinions of the various configurations of the test helicopter are the combined opinions of three NASA research pilots experienced in handling-qualities investigations, John P. Reeder, James B. Whitten, and Robert A. Champine. A fourth pilot also flew some approaches during the investigation. All the pilots agreed substantially on the points presented herein.

→ Standard deviation − 1 = Excess

Fract. deviation

Analysis of Flight Records

The method used in the statistical analysis is essentially that described in reference 5. The method required separating the records of the flight into two categories: pilots' control motions and motions of the helicopter. The pilots' control motions observed were longitudinal cyclic, lateral cyclic, pedals, and collective pitch. It should be noted here that for all the flight records analyzed the control motions used for maneuvering were relatively small compared with the total travel available. The helicopter motions were represented by the roll, pitch, and yaw angular velocities, and airspeed. In the present investigation the glide slope and localizer indications of the ILS instrument were also recorded and used in the statistical analysis.

In reference 5, the records of the helicopter's heading were used in the analysis. For the present report, it was believed that the position variation provided by the ILS localizer indications would give a more pertinent criterion of an approach, since the actual heading deviations depend on the wind which may be expected to be unsteady or to have variations with altitude. The glide slope was used since it is also one of the important parameters of the approach.

For the statistical analysis, the records were read at intervals of 1 second. A deviation was considered to exist if at a reading point of the time history the records indicated an excursion beyond the following preset limits: airspeed, ±3 knots; roll, pitch, and yaw angular velocities, ±0.01 radian/sec; ILS glide slope, ±20 percent; and ILS localizer, ±10 percent of the full scale instrument indications. A deviation in the pilot's control motion records was considered to exist if a given reading differed from the one preceding it by more than 0.5 percent of the total control travel. The total number of the deviations obtained from each record in this manner were then divided by the total number of reading points and the resulting number was labeled the fractional deviation for that record. A total of 200 to 300 readings for each record was made. The fractional deviations were then converted to a ratio of the standard deviation to the limits placed on the recorded values. This ratio minus one was termed the excess; thus one excess was obtained for each parameter recorded during an approach.

The algebraic sum of the excesses for the 10 recorded parameters obtained during an approach was called the cumulative excess. This cumulative excess has the property that the smaller its value the better the overall pilot-helicopter performance during the approach. Thus, a single parameter was obtained for each approach which provided a basis for comparison of the pilot-helicopter performance on the different approaches of a flight. In order to compare the pilot-helicopter performance through the use of the cumulative excess, it is necessary to remove all possibility of extraneous effects. In order to accomplish this, the "t"-test method of comparison described in reference 6 was used. This method and its application to the current investigation are described in detail in the appendix.

RESULTS AND DISCUSSION

The cumulative excess for each stability configuration and the reference configuration are presented in tables II to VI and the statistics used to determine the significance of the results are given below each table.

Data from representative flights of each configuration are plotted in figures 2 to 6. These figures show the excesses for each motion of the pilot and helicopter. In those cases where a negative value of an excess is present, the algebraic sum of the excesses is plotted and labeled a total. The cumulative excess for each condition may be obtained by adding the total for the pilot's motions to that of the helicopter's motions.

The Effects of Control Power on Handling Qualities

Very low damping.- Visual flights were conducted during which the damping of the helicopter about all axes was simultaneously reduced to very low values approaching zero or slightly negative values. For these flights, the helicopter's control power was kept at its original value. The pilots found the low damping to be highly undesirable. Visual maneuvers and preliminary instrument flights with the low damping showed the helicopter to be very difficult to control at times because even small initial disturbances resulted in large deviations in attitude and flight path. Even the measurements of damping at these low values were highly inconsistent because of the very high angular rates and the correspondingly high angular displacements resulting from the small control motions.

For these reasons the ILS approaches flown with low damping were limited to damping values only about as low as one-half the original value. It was felt that this value represented about the lowest damping that could be used for consistent results on the approaches. The flights of this investigation were flown at an airspeed of 45 knots because it was believed that the combination of a lower airspeed and low damping would make the flights unduly difficult.

One-half damping.- The pilots found a combination of one-half damping and one-half the original control power to be so difficult that no simulated blind flying was attempted. This combination was characterized by large control and helicopter motions, an uneasy feeling on the part of the pilot, and intense pilot concentration to maintain control. The results were found to improve as the control power was increased.

ILS approaches at the helicopter's original control power were feasible and were made. The results of flights with half damping and the original control power were, however, considerably poorer than results obtained with the basic helicopter. Table II shows the differences and the significant deterioration in results. Figure 2 is a plot of the cumulative excess for a representative flight (flight number 1) showing the results of four approaches. The first and last approaches were both flown with the helicopter in its original condition. The two intermediate approaches were flown at a damping value equal to half the original. When the first and last approaches are compared, it will be seen that the pilot's motions have been increased during the last approach, whereas the helicopter's motions remained essentially unchanged. The approaches at half damping both show increases in the pilot's motions and also in the helicopter's motions. This result indicates that the increase in pilot effort at half damping was required merely to perform the task, and the task was not so well performed. The pilot's opinions agreed with the results indicated and they further noted the unpleasant pronounced and continuous motion of the helicopter during the half-damping approaches.

As the control power was increased to about twice the value originally available in the helicopter while the damping was half its original value, the results of the approaches improved unexpectedly. All pilots were able to achieve better results with reduced damping and increased control power than with the original helicopter. Table III contains the statistical data for these flights and shows the improved performance. Figure 3 shows the results of one representative flight (flight number 5) indicating the marked decrease in pilots' motions with increased control power. The pilots felt that they had a better flying machine with twice the originally available control power, but had some reservations about the low damping. Apparently, somewhat questionable compensating characteristics developed that may have contributed to the improved performance. With the higher control powers greater accelerations were produced with small control deflections, permitting more rapid corrections to be made when flight instruments indicated a deviation from the desired attitude. This effect would probably become a disadvantage with less experienced pilots flying on instruments. In addition, at this low value of damping errors developed sooner and forced the pilot to act more rapidly. With the increased control power the pilot was able to make corrections with considerably less physical effort. The control motions made also had more effect, and the result was a better approach. Although less physical effort was required, more mental work was reported by the pilots. In general, they found that with the lower damping the helicopter was more difficult to trim and had a pronounced tendency to drift. During prolonged instrument flight, it might be expected that the combination of reduced damping and increased control power will not be as beneficial as indicated.

As the control power was increased further, to about four times the original power, the results again deteriorated. The results in figure 3 for four times the control power show the deterioration of all the helicopter's motions and the mild increase in the pilots' control motions. Some other flights indicated reduced pilots' motions but even greater increases in helicopter motions.

The pilots felt that a possible desirable combination of control powers for the three axes at one-half damping might be about one and one-half times the original power laterally, four times the original power longitudinally, and twice the original power directionally. These opinions are not surprising when the relative inertias about the three axes are considered. However, approaches with this trial arrangement showed no particular benefit over twice the control powers about all axes, as indicated in figure 3, and as commented on by the pilots. The pilots did feel, however, that twice the control power was slightly too powerful laterally and not sufficiently powerful longitudinally. Four times the longitudinal power is apparently too large a figure.

Examination of intermediate control powers with this amount of damping did not appear to be warranted since this damping value is known to be basically undesirable.

Original damping.- The results of control power variations at the helicopter's original damping are somewhat indefinite. Reduced control power was found to be definitely undesirable during visual flight. The pilots felt so strongly about this that no ILS approaches were flown in this condition. The pilots' comments on the performance of the helicopter during the ILS approaches indicated, in general, that they felt that four times the original control power made the machine too sensitive. At two times control power the results were more uncertain. The pilots at times felt they had improved performance and at other times noted no improvement at all. All the pilots, however, preferred the control characteristics provided by the higher power and thought they would need more control power than was available originally in order to have acceptable handling qualities for instrument flight.

The control powers chosen for trial as a possible desirable combination (one and one-half the original power laterally, four times longitudinally, and two times directionally) showed no definite improvement from either the pilots' opinions or statistical results. Figure 4 shows the results of a representative flight (flight number 7) and indicates the general effects of the various control powers. For this combination of control there is a reduction in control motion, as is usual with increases in control power. However, the helicopter's motions are increased in this condition and there is no net resulting gain.

When the control power was increased above the original value, there was no statistically significant improvement, as shown in table IV. As shown in the table, the use of the two different cyclic stick spring gradients had no effect on the results at twice the inherent control power. The pilots, however, did express a preference for the heavier springs.

High damping.- Table V presents the statistics of flights involving increases in control power while the damping had been increased to a level found desirable previously. There were no significant changes even when a control power four times the original value had been reached; thus it appears that at high damping a greater range of control power may be employed. Some unusual effects of different stick force gradient appeared at high damping and will be discussed later.

Figure 5 shows the results of a representative flight (flight number 12) involving high damping and various control powers. As is common with the higher powers, the pilots moved the controls fewer times. Their success, as represented by the helicopter motions, did not necessarily improve as a function of control power. Indeed, the powers which were chosen for trial as a possible desirable combination seemed to show a deterioration in results when compared with the original. The end result, however, was no significant difference.

Additional Factors Affecting the Control Power Investigation

Pilot technique.- The flights conducted revealed a side effect of the control power variations that was a result of pilot technique. Three pilots (pilots A, C, and D) used their fingers for control of the cyclic stick while resting their forearm on their knee. One pilot (pilot B) flew with his arm unsupported and held the cyclic control firmly with his whole hand. For the precision involved in the ILS approach, pilot A reported a desire for a considerable increase in control power. Pilot B felt that only a slight increase was desirable and thought that double the normal value was excessive and contributed to overcontrolling and lack of precision. Figure 6 shows the results of three flights, one by pilot A and two by pilot B. In figure 6(a) (flight number 5), when the damping was reduced by one-half and the control power was varied from its original value to twice that value, the results are considerably and significantly improved by the increased control power. In figure 6(b) (flight number 4) some improvement in the pilot's motions is noted for the same conditions, but some deterioration in the helicopter's motion is also noted. For the flight of figure 6(b) there is no statistically significant difference between the original and increased control powers. Pilot B later flew some approaches using the finger technique with essentially the same results as pilot A as shown by comparison of figures 6(c) (flight number 10) and 6(a) (flight number 5).

A pilot using his fingers is capable of much finer control since the fingers are a much finer instrument than the whole hand and arm. The finger technique also has the advantage of resting most of the arm which helps make the approach somewhat less tiring. However, this technique is satisfactory only if the control power is such that no very large motions or large stick forces are required during normal flight. As mentioned earlier, the analysis in this paper is based on flight records of precision tasks which required very small control motions.

Cyclic control-force gradient.- The cyclic stick and pedals had only an electrical link with the swashplate and tail rotor. The forces felt by the pilot were those supplied by centering springs. For this investigation, two sets of cyclic stick springs were used: one with a gradient of 5 ounces per inch and the other with a gradient of 1 pound per inch, both measured at the center of the stick grip.

Pilots generally favored the feel provided by higher gradient, particularly at the higher control powers. In flights conducted with one-half damping and one-half control power, in which the controls were sometimes moved to full travel and often through large amplitudes, the higher spring gradient was, however, felt to be unsatisfactory. Statistically, little difference was noted between the two gradients. Statistical comparison (table VI) of two conditions (high damping with original control power and high damping with four times original control power) with light springs showed an improvement resulting at the higher control power. A comparison of the same two conditions, but with heavier springs, shows some apparent improvement at higher control powers, but the difference was not significant. Pilot opinion in general favored the helicopter with high control power when light springs were used. However, with heavy springs and high control power, the pilots commented on the increased level of concentration required to prevent a jerky response and did not particularly feel they had a better flying machine than with the helicopter at high damping and the original control power. Although considerably more work would have to be done on force gradients and other control force characteristics before definite conclusions on optimum gradients could be reached, this investigation shows that the effects of changes within the range tested here are secondary. This result is compatible with previous experience which has suggested that, although having a definite gradient produced improvements over having no gradients, further changes in gradient usually produce no sharply defined effects on ease of flying.

Summary Charts of Effects of Damping and Control Power

In order to examine the overall effects of all the individual tests covered in this investigation, summary charts are presented. These charts are presented in two ways: first, by the direct use of damping and control power, and second, by using response quantities and damping.

Definitions of handling-qualities classifications.- The following classifications are listed and defined to facilitate discussion of the degree with which the variations in control power and damping affected the desirability of the handling qualities:

Desirable - Good handling qualities for instrument flight operations

Acceptable - Acceptable for instrument flight operations

Minimum acceptable - Acceptable for emergency instrument flight operations only

Marginal - Acceptable for visual flight operations only

Unacceptable - Unacceptable even for visual flight operations.

Boundaries of the classifications.- The general effects of combinations of damping and control power are summarized in figures 7 and 8. Figure 7 contains plots of the various combinations of control power and damping listed and (through use of the previously defined terms) contains an indication of their desirability. The points plotted represent actual test conditions, and the boundaries are the results of estimates based on the pilots' opinions together with the statistical results at adjacent test points. Both the present results and those of references 1 and 2 are used. These boundaries are necessarily interpolated or even extrapolated from the results and are therefore not sharply defined lines. It is always doubtful whether sharp divisions can be made covering such quantities as handling qualities. However, the areas do represent good estimates providing an overall picture of the results and may be expected to be reasonably reliable.

The initial angular acceleration about the various axes is directly proportional to the control-power multiples shown in figure 8, since the inertia is fixed (for example, twice the control power about any axis will produce twice the initial angular acceleration). For convenience in applying the results to other aircraft, a second abscissa scale indicating the ratio of control power to inertia has been marked on figure 7.

The curves of figure 8 present essentially the same information as figure 7 except that the control power variation is replaced by the pertinent response quantities similar to those referred to in reference 8. Figure 8(a) shows the effects of control power as represented by the pitch attitude change obtained in the first second following a 1-inch longitudinal cyclic stick displacement. The values are those calculated by means of reference 7 for the airspeed used in the flight tests, 45 knots. Since airspeed has only a very small effect on the pitch attitude change, this parameter was selected in preference to others which would also reflect variations in control power, but which would be more susceptible to change with airspeed (for example, normal acceleration).

Figure 8(b) shows the results about the roll axis plotted in terms of the maximum angular roll velocity reached. It will be noted that the requirement of reference 8 (shown in figure 8) is not adequate to limit a great area of undesirable conditions. The maximum angular velocity is also a function of both damping and control power. In order to separate these two variables, figure 8(c) is presented. The control power in this case is represented by the roll attitude change in the first second following a 1-inch lateral stick displacement. This method is a more reliable measure of control power since the angular velocity will not be large up to 1 second and the damping will have only a small effect on the attitude change.

Figure 8(d) shows the results in yaw. The requirements of reference 8 are shown and again there are large undesirable areas which are not excluded by these requirements.

The application of the boundaries.- A survey of data available on various helicopters and some other VTOL configurations indicates that the handling-qualities boundaries may be expected to apply reasonably well to low-speed aircraft in the range of 2,000 to 10,000 pounds gross weight. Based on examination of the problem it may be expected, however, that, when a larger range of gross weights is considered, the control power boundaries will shift with aircraft size, the smaller aircraft requiring the higher ratios of control power to inertia. Thus, for the larger aircraft, both the minimum and maximum initial angular acceleration values found desirable may be somewhat lower than those shown on the charts. It should be possible to apply the values shown on the charts to larger machines by considering some factor such as ratio of gross weight, inertia, or other typical characteristic of larger size. In addition, other factors (such as low degree of weathercock stability) may affect the need for initial angular acceleration and thus shift the range of desirable values of control power for a specific configuration. The determination of these factors, however, is beyond the scope of the present paper. Similarly, examination of the problem suggests that the minimum damping to inertia ratios will vary when extreme ranges of size are considered. With these same reservations, the charts should also have application to other vertical-take-off-and-landing (VTOL) aircraft as well as the pure helicopter because of the basic nature of the parameters.

The charts can be used as a guide during initial design by first locating, on the abscissa of figure 7, the ratio of control power to inertia of a proposed helicopter or VTOL. The damping-to-inertia ratio can then be located on the ordinate of the figure and an estimate of the handling qualities can be obtained.

The ratio of damping to inertia can be determined by first finding the damping moment about each axis, in units of foot-pounds per radian per second, and then dividing by the inertia about that axis in units of slug-ft^2. An increase in damping (or control power) supplied by automatic devices can also be considered by adding the moment caused by this equipment to the basic value before finding the ratio needed to enter the charts.

Of the possible ways of using the charts, this particular method of application was considered most appropriate at present since it has the advantage that it enables the use of the charts for both tandem- and single-rotor helicopters, as well as other VTOL configurations, on roughly the same basis. In cases where an unusual control system other than the cyclic stick is used, it may be more appropriate to consider percent of control travel or other similar criterion rather than the inches of travel.

For a machine in the flight stage it may be more convenient to make use of the charts in figure 8. At this stage the inertia will usually be known or can be determined. The damping can be determined from flight tests, as can the response quantities of figure 8. These charts can then be used as a general guide to determine the direction in which a change may be made to improve handling qualities or to estimate the effect on handling qualities of other design changes.

CONCLUDING REMARKS

An investigation of the effects of combinations of helicopter control power and damping has been conducted. The improvement in handling qualities as the damping is increased, which is clearly shown in previous investigations, is further confirmed by these results. The effects of control power variations are not equally definite. The control powers found to be desirable fell in a range which increased slightly as the damping was increased as long as both control power and damping were above minimum values. However, the control power becomes excessive at high values while, as noted previously, the highest damping examined contributed to improvement in the handling qualities.

If the pilot used his fingers for holding and controlling the cyclic stick while resting his elbow on his knee, he had a much finer means of control and was more successful than if he held the stick with his hand and moved both hand and arm for control.

The effects of changes in the cyclic stick force gradient within the range tested are secondary.

Charts have been presented summarizing the effects on handling qualities of both control power and damping and outlining areas from unacceptable for visual flight to desirable for instrument flight. It is expected that these charts may be generally applicable to aircraft in the 2,000- to 10,000-pound range of gross weights. Where larger ranges of gross weights have to be dealt with, it is anticipated that some reduction in the range of control power indicated as a function of gross weight, inertia, or physical dimensions will prove desirable.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., May 7, 1959.

APPENDIX

THE STATISTICAL COMPARISON OF DATA

For the evaluation of the effects of changes in stability configuration, the flight program was organized so that the first and last approaches in a flight were flown with the reference configuration. A direct comparison of the cumulative excess measured with a configuration change with the values of cumulative excess measured in the reference configuration proved to be not feasible, however, in view of a consistent tendency for the overall pilot-helicopter performance to be better on the last approach than on the first. The cause of this trend apparently lies in the exigencies of scheduling and operation which often necessitated long delays between flights. Despite familiarization exercises prior to data collection, it is considered that there was a certain amount of pilot learning or refamiliarization during the course of a flight and that this factor accounts for the observed trend in values of cumulative excess. Because of this trend, the tests of significance used in reference 5 were modified in the present study, and a standard procedure more adapted to the present set of data was employed. This procedure utilized the so-called "null-hypothesis" method and the "t-test" as outlined in reference 6.

Comparison by Use of the Null Hypothesis

In order to evaluate the effects of configuration changes, the null-hypothesis method requires the setting up of an hypothesis, or assumption about helicopter approaches, and use of a statistical test to decide whether a particular set of approaches differs significantly from the assumption. The hypothesis made is that changes in stability configuration have no effect on the pilot's task or the helicopter performance. If this hypothesis were true, it would be expected that the cumulative excess, which measures pilot's task and helicopter performance, would not change and that, if a value measured in the changed configuration differs from one for the standard configuration, this difference is due not to the changed configuration but to random causes which affect the determination of a value of cumulative excess. If differences are determined by chance alone, it would be expected that a number of such differences would be randomly distributed about a mean of zero. A question of statistical estimation is thus indicated: For a particular change in configuration if the mean value of a number of differences is given, does it differ from zero by an amount which is greater than should be expected on the basis of chance alone? The "t" test provides a standard technique for assessing the significance of an observed mean of a number of differences and thus of judging whether the null hypothesis is violated.

The "t" Test

The "t" test is a general test for assessing the significance of the difference between an observed mean value of some quantity and the expected value of the mean. Based on the properties of a normal distribution, use of the test requires the calculation of three quantities or statistics which in the present case are characteristic of the set of differences x_i being judged. These statistics include the mean $\bar{x}$ of the set of differences, the best estimate s of the standard deviation of the set, and $s_{\bar{x}}$, the best estimate of the standard deviation of $\bar{x}$. The value of t is then defined as the ratio of the difference between the observed mean and the assumed mean (zero) to the standard deviation of the mean. These quantities are conveniently computed from the formulas:

$$\bar{x} = \frac{1}{n'} \Sigma(x_i)$$

$$s^2 = \frac{1}{n' - 1} \Sigma(x_i - \bar{x})^2$$

$$= \frac{n'\Sigma(x_i)^2 - (\Sigma x_i)^2}{n'(n' - 1)}$$

$$s_{\bar{x}} = \frac{s}{\sqrt{n}}$$

$$t = \frac{\bar{x}}{s_{\bar{x}}}$$

where

x_i a difference of cumulative excess

n' number of differences

$\bar{x}$ mean of differences of cumulative excess

s best estimate of standard deviation of differences of cumulative excess

$s_{\bar{x}}$ best estimate of standard deviation of $\bar{x}$

n number of degrees of freedom, $n' - 1$

and the symbol Σ is used to indicate summation over the sample range from $i = 1$ to $i = n'$.

The test of the hypothesis is made by comparing the calculated value of t with a value t_n obtained from standard tables. (See, for example, table IV of ref. 6.) As used in the present study the value of t_n selected corresponds to a probability of 0.05 or 1 in 20 for the number of degrees of freedom n available for the test. The values of n and t_n are shown on each of the result tables of the present paper. The criteria used are: if $t < t_n$, accept hypothesis; if $t \gtreqless t_n$, reject hypothesis. Acceptance of the hypothesis thus implies that the changes in stability configuration have had no effect; rejection, on the other hand, implies that the differences in cumulative excess are too large to be explained by chance alone and thus presumably are the result of the stability configuration change.

Limitations of the Comparison Procedure

Use of a statistical technique to assess the effects of a given change in damping or control power does not, of course, guarantee that in any particular instance a large value of the mean difference is the result of the change in configurations, not of random effects nor, on the other hand, does the test provide a guarantee that a small value of the mean is not the result of random effects which have operated to obscure the effects of a configuration change. Selection of the probability level of 0.05 does imply, however, that, if the test is used in a number of cases to accept or reject, the decision will be wrong on the average only once in about 20 times. Furthermore, it takes into account the relative levels of significance which can be attached to tests where only three or four comparisons are available as compared with tests where a larger number of comparisons can be used.

Comparison of First and Last Approaches

As an example of the procedure and to illustrate the need for this particular method of analysis, a comparison of the first and last approaches in 12 flights is given in table VII. The mean difference in cumulative excess is -1.743 and is indicative of improvement in overall performance. The value of t is 2.33 which exceeds the value of $t_n = 2.20$. The improvement is therefore judged to be real and, as stated previously, is ascribed to pilot learning. Thus, even though the first and last approaches were flown in a standard configuration, comparison with the standard is complicated by the learning trend, and some loss of precision has been sustained in making comparisons. The statistical technique described in this appendix and considered applicable to these circumstances was employed.

REFERENCES

1. Whitten, James B., Reeder, John P., and Crim, Almer D.: Helicopter Instrument Flight and Precision Maneuvers as Affected by Changes in Damping in Roll, Pitch, and Yaw. NACA TN 3537, 1955.

2. Reeder, John P., and Whitten, James B.: Some Effects of Varying the Damping in Pitch and Roll on the Flying Qualities of a Small Single-Rotor Helicopter. NACA TN 2459, 1952.

3. Amer, Kenneth B.: Theory of Helicopter Damping in Pitch or Roll and a Comparison With Flight Measurements. NACA TN 2136, 1950.

4. Gustafson, F. B., and Tapscott, Robert J.: Methods for Obtaining Desired Helicopter Stability Characteristics and Procedures for Stability Predictions. NACA Rep. 1350, 1958. (Supersedes NACA TN 3945.)

5. Salmirs, Seymour, and Tapscott, Robert J.: Instrument Flight Trials With a Helicopter Stabilized in Attitude About Each Axis Individually. NACA TN 3947, 1957.

6. Fisher, R. A.: Statistical Methods for Research Workers. G. E. Stechart & Co., 8th ed., 1941.

7. Amer, Kenneth B.: Method for Studying Helicopter Longitudinal Maneuver Stability. NACA Rep. 1200, 1954. (Supersedes NACA TN 3022.)

8. Anon.: Military Specification - Helicopter Flying Qualities, Requirements for. Military Specification, MIL-H-8501, Nov. 5, 1952.

TABLE I.- PHYSICAL CHARACTERISTICS OF THE TEST HELICOPTER

Gross weight, lb	5,500
Moments of inertia:	
Pitch, slug-ft^2	7,000
Roll, slug-ft^2	2,000
Yaw, slug-ft^2	5,000
Number of blades in main rotor	3
Rotor rotational speed, radians/sec	19.4
Rotor diameter, ft	48
Height of rotor hub with respect to center of gravity, ft	6.5
Blade mass factor	9
Horizontal stabilizer area, ft^2	8
Control travel:	
Longitudinal cyclic, in.	13.6
Lateral cyclic, in.	13.6
Pedal, in.	4.75
Control power:	
Pitch, ft-lb/in. of control travel	508
Roll, ft-lb/in. of control travel	474
Yaw, ft-lb/in. of control travel	4,140
Damping:	
Pitch, ft-lb/radians/sec	4,640
Roll, ft-lb/radians/sec	2,495
Yaw, ft-lb/radians/sec	10,600

TABLE II.- COMPARISON BETWEEN ORIGINAL AND ONE-HALF DAMPING

[Original control power; 1 lb/in. spring gradient]

Flight	Comparison	Original	One-half damping	Difference	
				x	x^2
1	1	5.63	9.01	3.38	11.42
1	2	6.79	9.01	2.22	4.93
1	3	7.17	9.01	1.84	3.39
1	4	5.63	9.72	4.09	16.73
1	5	6.79	9.72	2.93	8.58
1	6	7.17	9.72	2.55	6.50
2	7	8.37	11.66	3.29	10.82
2	8	7.79	11.66	3.87	14.98
2	9	8.37	6.68	-1.69	2.86
2	10	7.79	6.68	-1.11	1.23
3	11	5.94	8.56	2.62	6.86
3	12	5.67	8.56	2.89	8.35
---	$n' = 12$	----	-----	$\Sigma(x) = 26.88$	$\Sigma(x^2) = 96.65$

Computed statistics:

$n = 11$ $\qquad \dfrac{s}{\sqrt{n'}} = 0.526$

$\bar{x} = 2.24$ $\qquad t = 4.26$

$s = 1.82$ $\qquad t_n = 2.20$

TABLE III.- COMPARISON BETWEEN ORIGINAL AND HALF DAMPING WITH 2 TIMES CONTROL POWER

[1 lb/in. spring gradient]

Flight	Comparison	Original	Half damping with 2 times control power	Difference	
				x	x^2
3	1	5.94	4.42	-1.52	2.31
3	2	5.94	5.32	-.62	.38
3	3	5.67	4.42	-1.25	1.56
3	4	5.67	5.32	-.35	.12
5	5	9.03	5.17	-3.86	14.90
5	6	8.57	5.17	-3.40	11.56
6	7	7.39	3.82	-3.57	12.74
6	8	5.73	3.82	-1.91	3.65
10	9	5.42	3.32	-2.10	4.41
10	10	7.91	3.32	-4.59	21.07
--	$n' = 10$	----	----	$\Sigma(x) = -23.17$	$\Sigma(x^2) = 72.70$

Computed statistics:

$n = 9$ $\qquad \frac{s}{\sqrt{n'}} = 0.460$

$\bar{x} = -2.32$ $\qquad t = 5.05$

$s = 1.46$ $\qquad t_n = 2.26$

TABLE IV.- COMPARISON BETWEEN ORIGINAL POWER, 2 TIMES CONTROL POWER, AND 4 TIMES CONTROL POWER

[Original damping]

(a) 5 oz/in. spring gradient

Flight	Comparison	Original	Two times control power	Difference	
				x	x^2
13	1	6.88	5.83	-1.05	1.10
14	2	9.17	11.42	2.25	5.06
15	3	6.55	6.98	.43	.18
--	n' = 3	----	----	$\Sigma(x) = 1.63$	$\Sigma(x^2) = 6.34$

Computed statistics:

$n = 2$ $\frac{s}{\sqrt{n'}} = 0.954$

$\bar{x} = 0.543$ $t = 0.569$

$s = 1.65$ $t_n = 4.30$

(b) 1 lb/in. spring gradient

Flight	Comparison	Original	Two times control power	Difference	
				x	x^2
7	1	6.72	7.53	0.81	0.66
7	2	1.37	7.53	6.16	37.95
8	3	5.05	.38	-4.67	21.81
8	4	1.03	.38	-.65	.42
9	5	7.49	1.13	-6.36	40.45
9	6	4.76	1.13	-3.63	13.18
---	n' = 6	----	----	$\Sigma(x) = -8.34$	$\Sigma(x^2) = 114.47$

Computed statistics:

$n = 5$ $\frac{s}{\sqrt{n'}} = 1.852$

$\bar{x} = -1.39$ $t = 0.751$

$s = 4.54$ $t_n = 2.57$

(c) 1 lb/in. spring gradient

Flight	Comparison	Original	Four times control power	Difference	
				x	x^2
7	1	6.72	1.66	-5.06	25.60
7	2	1.37	1.66	.29	.08
8	3	5.05	.75	-4.30	18.49
8	4	1.03	.75	-.28	.08
9	5	7.49	5.03	-2.46	6.05
9	6	4.76	5.03	.27	.07
---	n' = 6	----	----	$\Sigma(x) = -11.54$	$\Sigma(x^2) = 50.37$

Computed statistics:

$n = 5$ $\frac{s}{\sqrt{n'}} = 0.861$

$\bar{x} = -1.923$ $t = 2.24$

$s = 2.11$ $t_n = 2.57$

TABLE V.- COMPARISON BETWEEN ORIGINAL AND TWO TIMES CONTROL POWER

[High damping]

(a) 5 oz/in. spring gradient

Flight	Comparison	Original	Two times control power	Difference	
				x	x^2
16	1	7.73	8.16	0.43	0.18
17	2	5.66	9.72	4.06	16.48
17	3	5.66	4.73	-.93	.86
17	4	8.48	9.72	1.24	1.54
17	5	8.48	4.73	-3.75	14.06
18	6	13.50	14.81	1.31	1.72
19	7	7.74	5.83	-1.91	3.65
19	8	6.34	5.83	-.51	.26
---	$n' = 8$	-----	-----	$\Sigma(x) = -0.06$	$\Sigma(x^2) = 38.75$

Computed statistics:

$n = 7$ $\qquad \dfrac{s}{\sqrt{n'}} = 0.832$

$\bar{x} = -0.008$ $\qquad t = 0.010$

$s = 2.35$ $\qquad t_n = 2.37$

(b) 1 lb/in. spring gradient

Flight	Comparison	Original	Two times control power	Difference	
				x	x^2
11	1	8.91	1.31	-7.60	57.76
11	2	4.03	1.31	-2.72	7.40
12	3	3.62	1.60	-2.02	4.08
12	4	3.23	1.60	-1.63	2.66
---	$n' = 4$	-----	----	$\Sigma(x) = -13.97$	$\Sigma(x^2) = 71.90$

Computed statistics:

$n = 3$ $\qquad \dfrac{s}{\sqrt{n'}} = 1.389$

$\bar{x} = -3.49$ $\qquad t = 2.52$

$s = 2.78$ $\qquad t_n = 3.18$

TABLE VI.- COMPARISON BETWEEN ORIGINAL AND FOUR TIMES CONTROL POWER

[High damping]

(a) 5 oz/in. spring gradient

Flight	Comparison	Original	Four times control power	Difference	
				x	x^2
16	1	7.73	4.27	-3.46	11.97
17	2	5.66	5.91	.25	.06
17	3	8.48	5.91	-2.57	6.60
19	4	7.74	5.39	-2.35	5.52
19	5	6.34	5.39	-.95	.90
---	n' = 5	----	----	$\Sigma(x) = -9.08$	$\Sigma(x^2) = 25.05$

Computed statistics:

$n = 4$ $\frac{s}{\sqrt{n'}} = 0.654$

$\bar{x} = -1.816$ $t = 2.78$

$s = 1.46$ $t_n = 2.78$

(b) 1 lb/in. spring gradient

Flight	Comparison	Original	Four times control power	Difference	
				x	x^2
11	1	8.91	1.36	-7.55	57.00
11	2	4.03	1.36	-2.67	7.13
12	3	3.62	2.05	-1.57	2.46
12	4	3.23	2.05	-1.18	1.39
---	n' = 4	----	----	$\Sigma(x) = -12.97$	$\Sigma(x^2) = 67.98$

Computed statistics:

$n = 3$ $\frac{s}{\sqrt{n'}} = 1.47$

$\bar{x} = -3.24$ $t = 2.20$

$s = 2.94$ $t_n = 3.18$

TABLE VII.- COMPARISON OF THE CUMULATIVE EXCESS OF THE FIRST AND LAST RUNS

Flight	Comparison	First run	Last run	Difference	
				x	x^2
1	1	5.63	7.17	1.54	2.37
2	2	8.37	7.89	-.48	.23
3	3	5.94	5.67	-.27	.07
4	4	11.80	7.10	-4.70	22.09
5	5	9.03	8.57	-.46	.21
6	6	7.39	5.73	-1.66	2.76
7	7	6.72	1.37	-5.35	28.62
8	8	5.05	1.03	-4.02	16.16
9	9	7.49	4.76	-2.73	7.45
10	10	5.42	7.91	2.49	6.20
11	11	8.91	4.03	-4.88	23.81
12	12	3.62	3.23	-.39	.15
--	n' = 12	-----	----	$\Sigma(x) = -20.91$	$\Sigma(x^2) = 110.12$

Computed statistics:

$n = 11 \qquad \frac{s^2}{n'} = 0.558$

$\bar{x} = -1.743 \qquad \frac{s}{\sqrt{n'}} = 0.747$

$$s = 2.59 \qquad t = \frac{\bar{x}}{s/\sqrt{n'}} = \frac{1.743}{0.747} = 2.33$$

$t_n = 2.20$

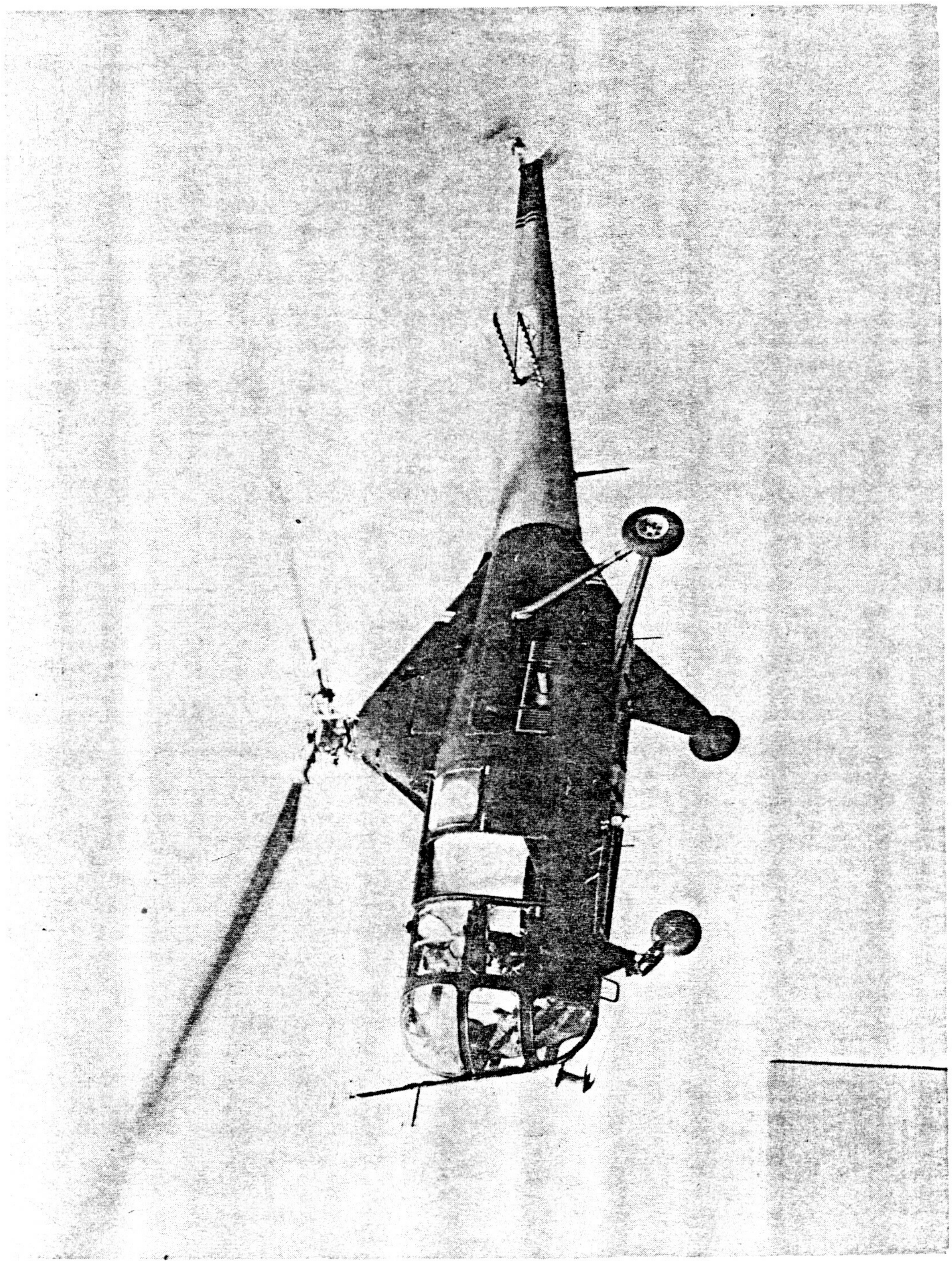


Figure 1.- Helicopter used in investigation.

L-88302

Figure 1.- Helicopter used in investigation. L-88302

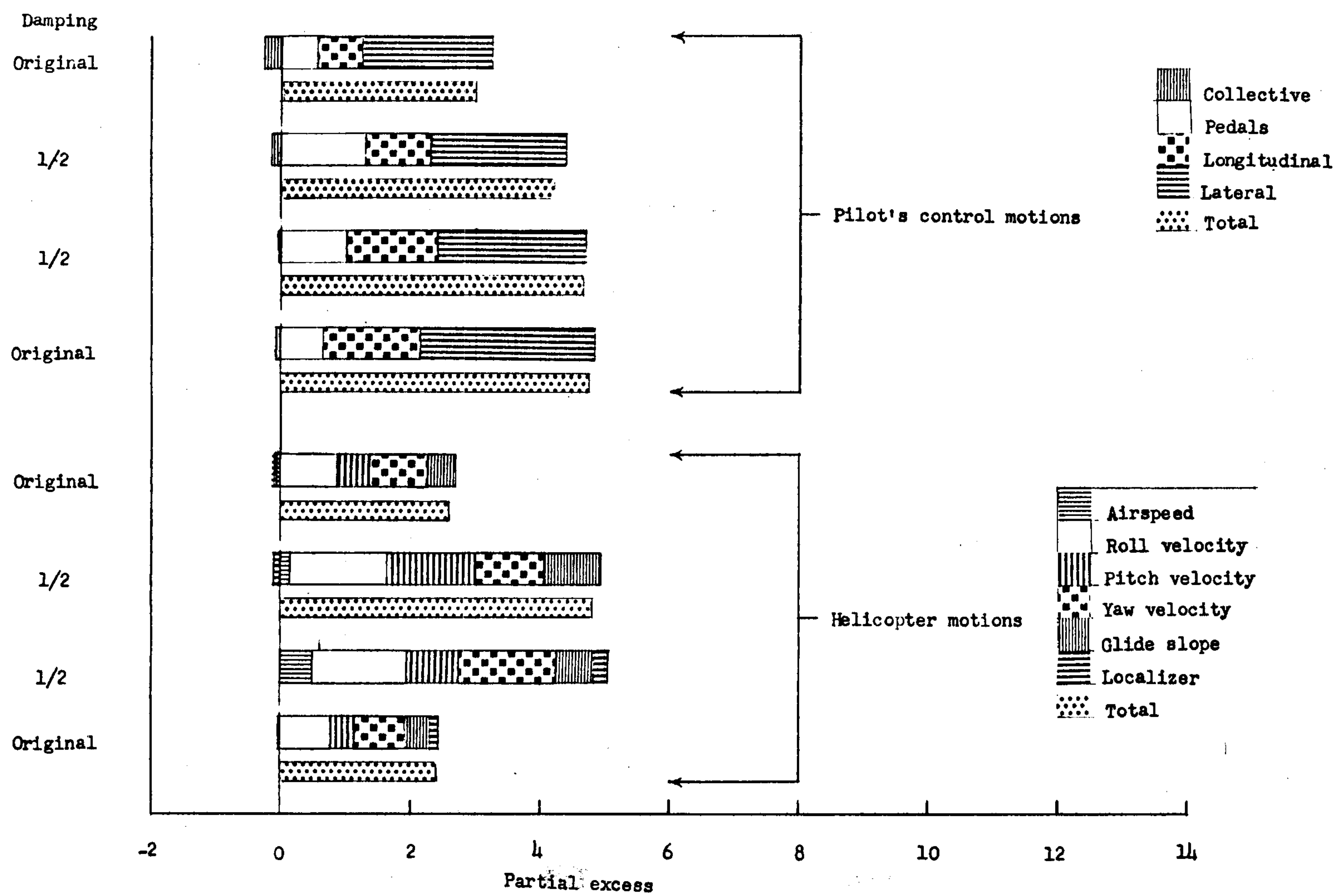


Figure 2.- Pilot's and helicopter's motions at original control power with original and half damping.

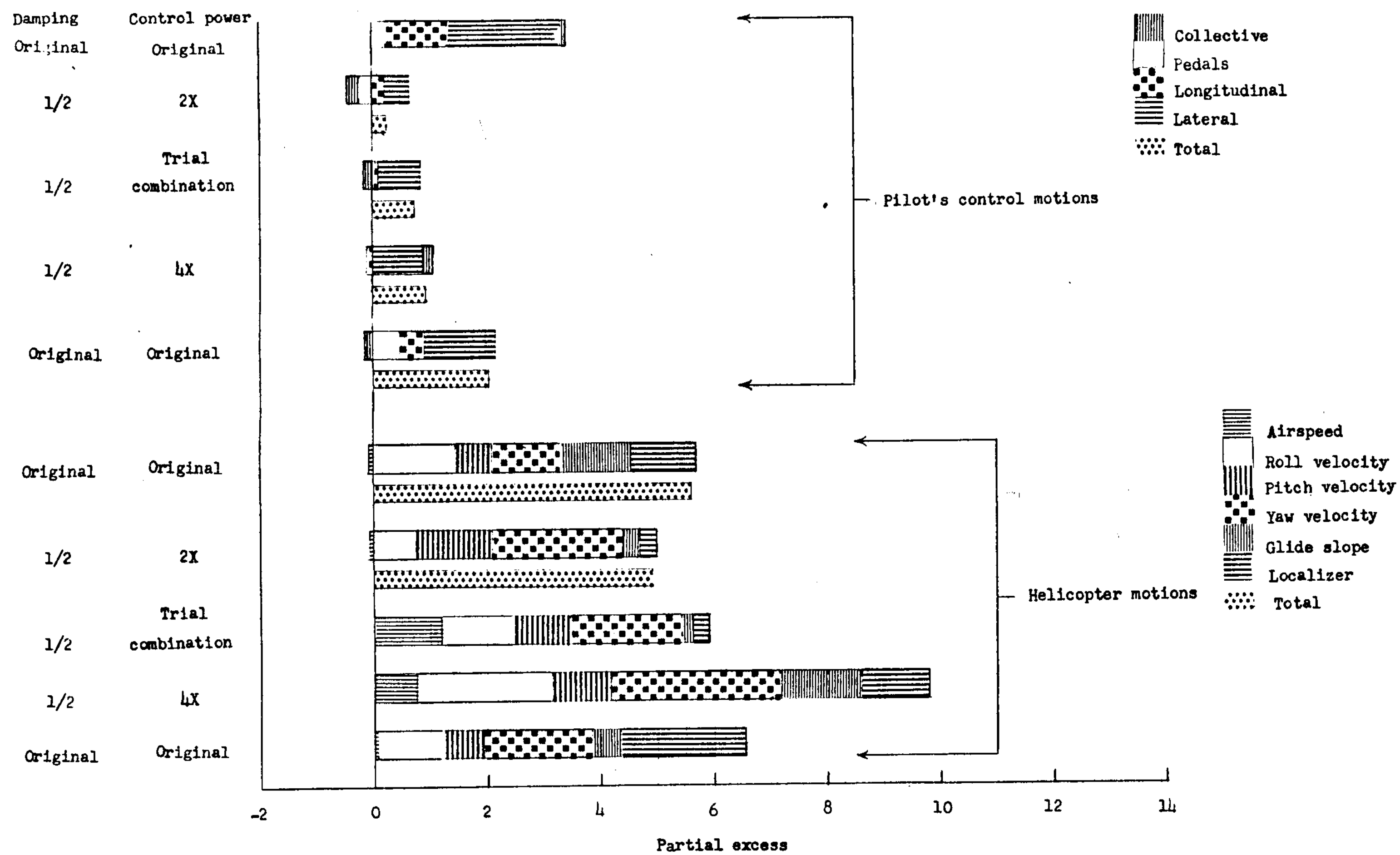


Figure 3.- Pilot's and helicopter's motions at half damping and various control powers.

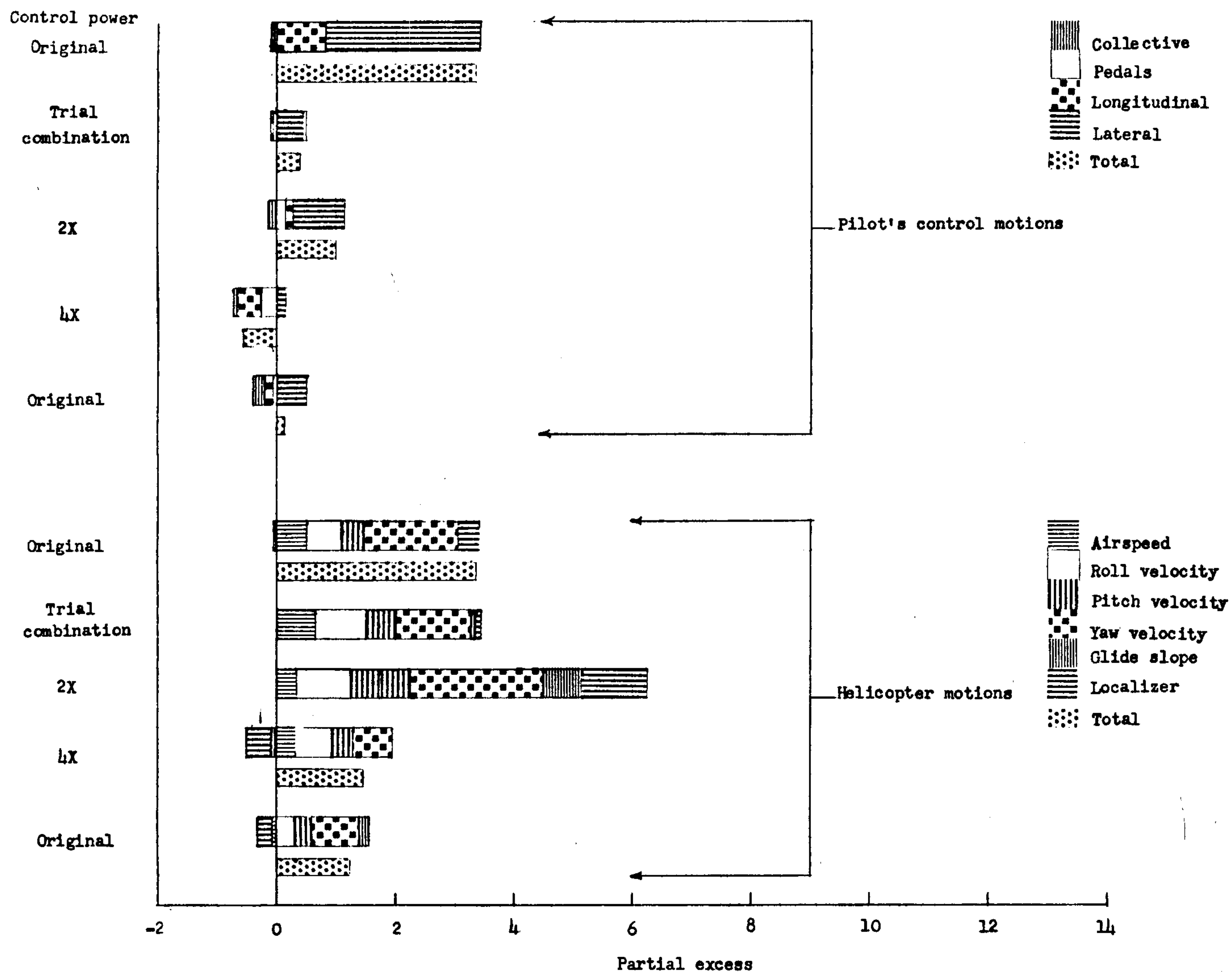


Figure 4.- Pilot's and helicopter's motions with original damping and various control powers.

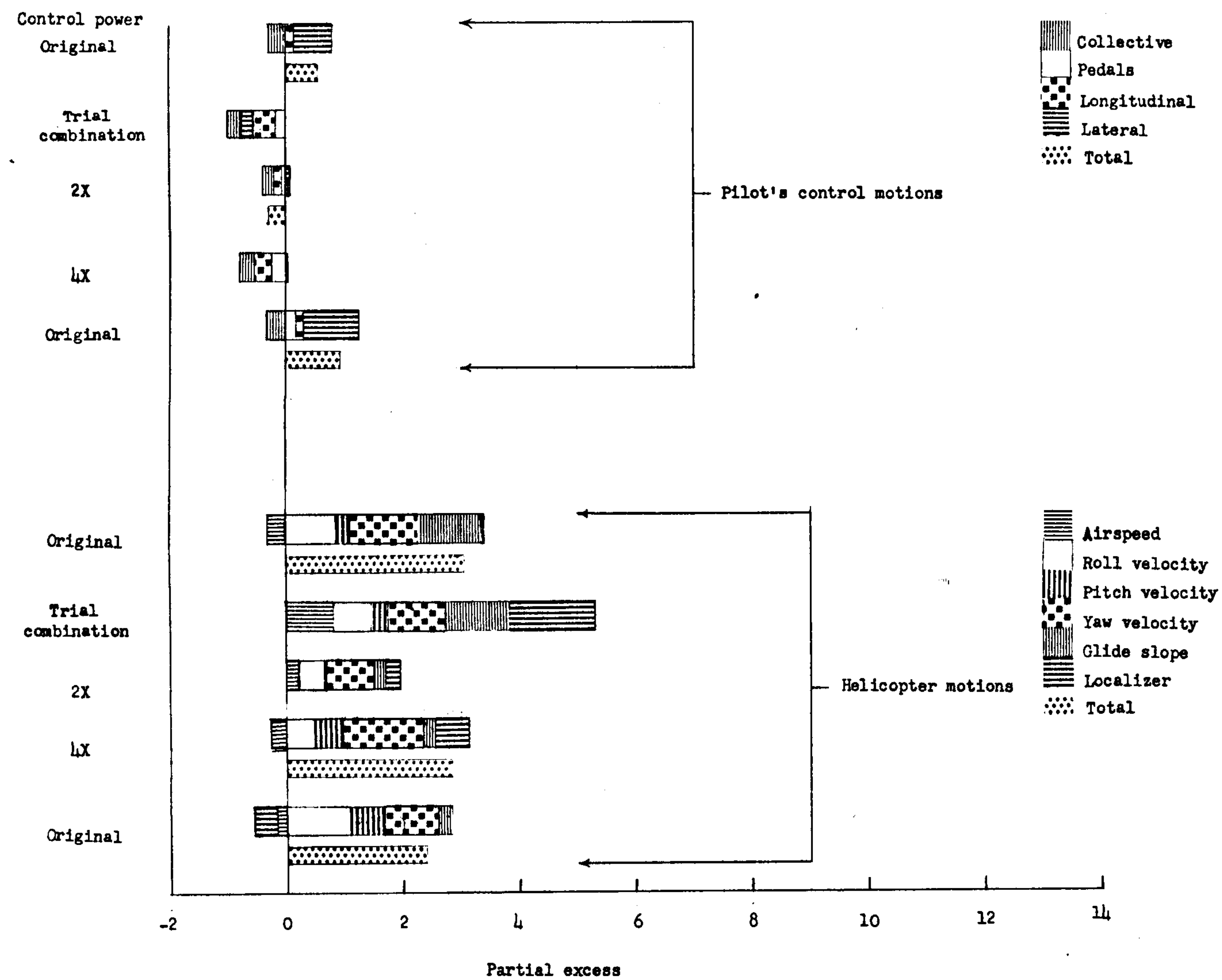
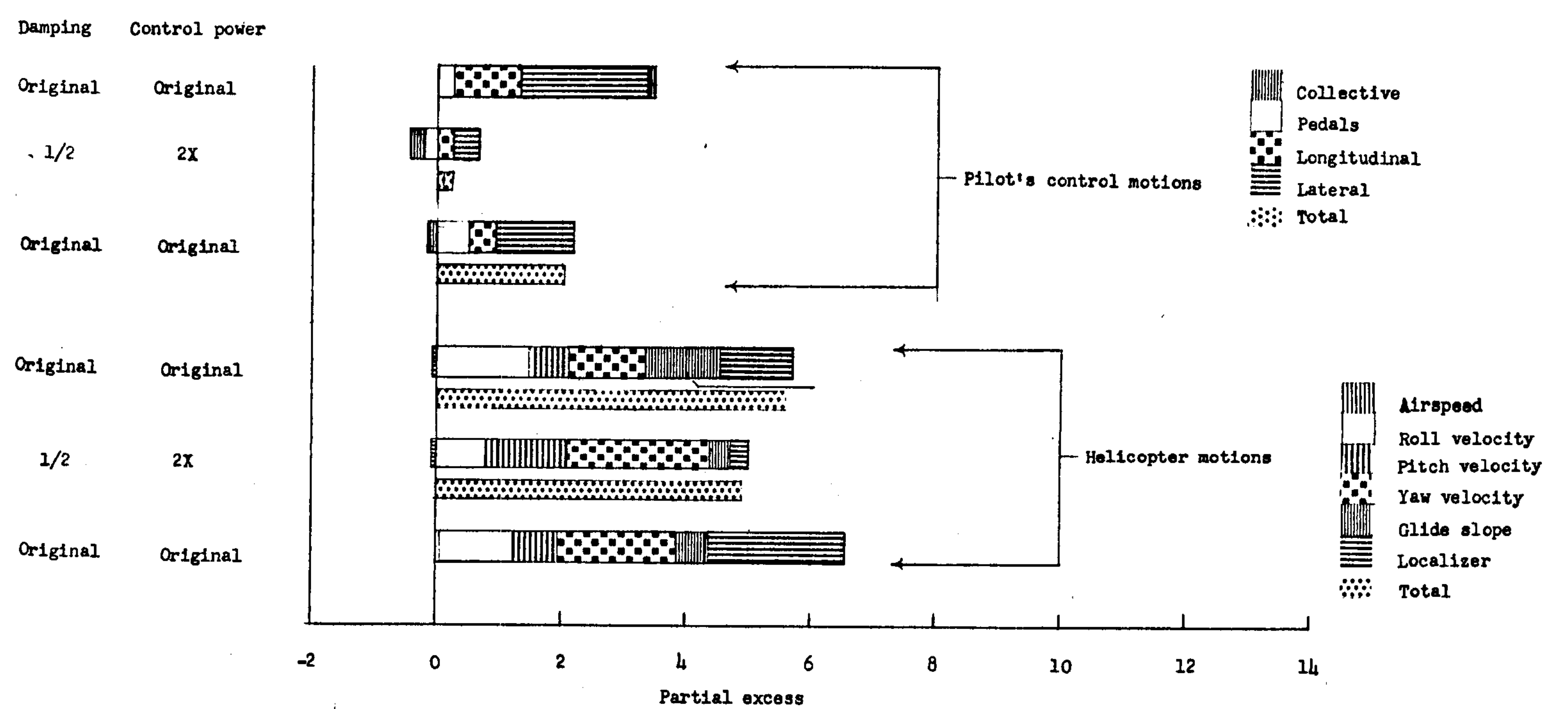
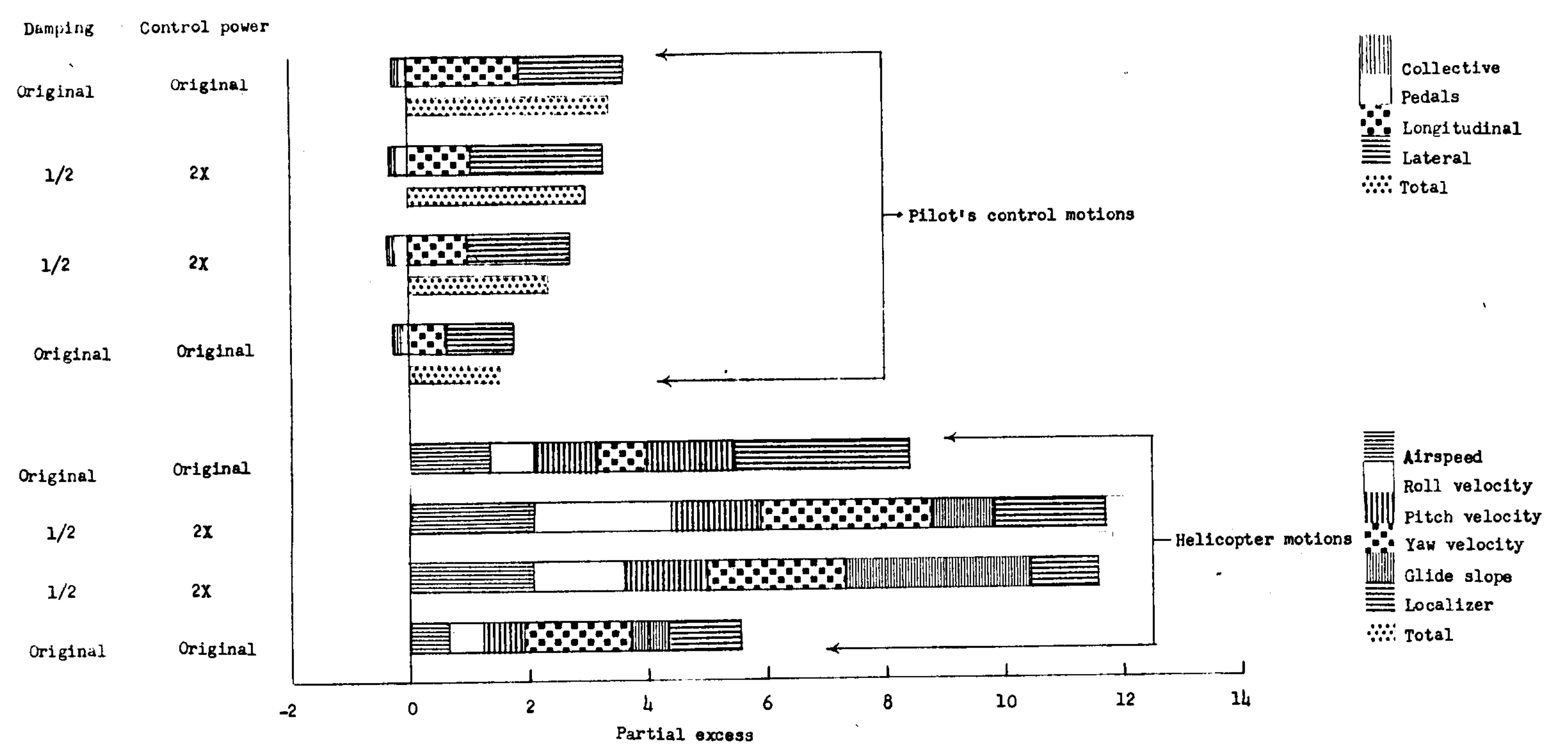


Figure 5.- Pilot's and helicopter's motions with high damping at various control powers.



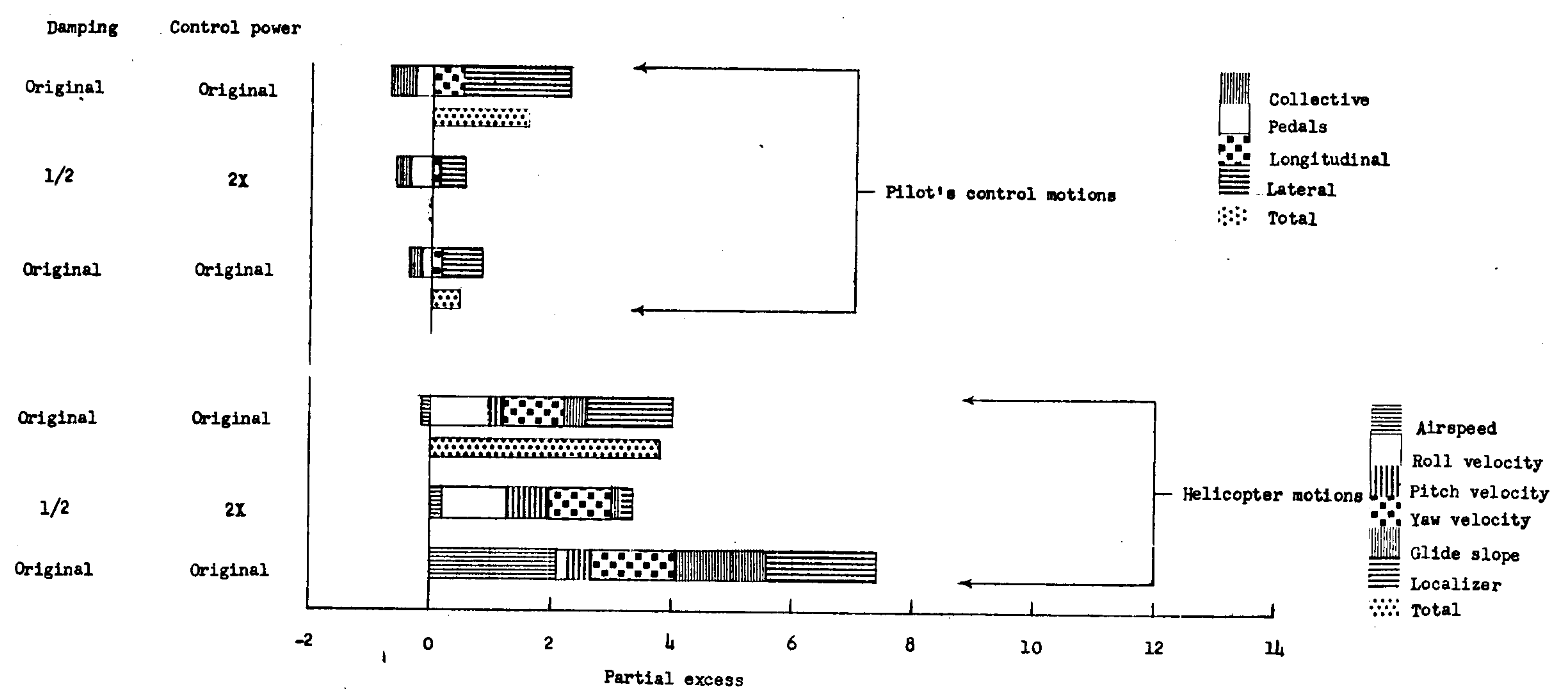
(a) Pilot A (finger technique).

Figure 6.- Effects of pilot technique at various combinations of control power and damping.



(b) Pilot B (hand technique).

Figure 6.- Continued.



(c) Pilot B (finger technique).

Figure 6.- Concluded.

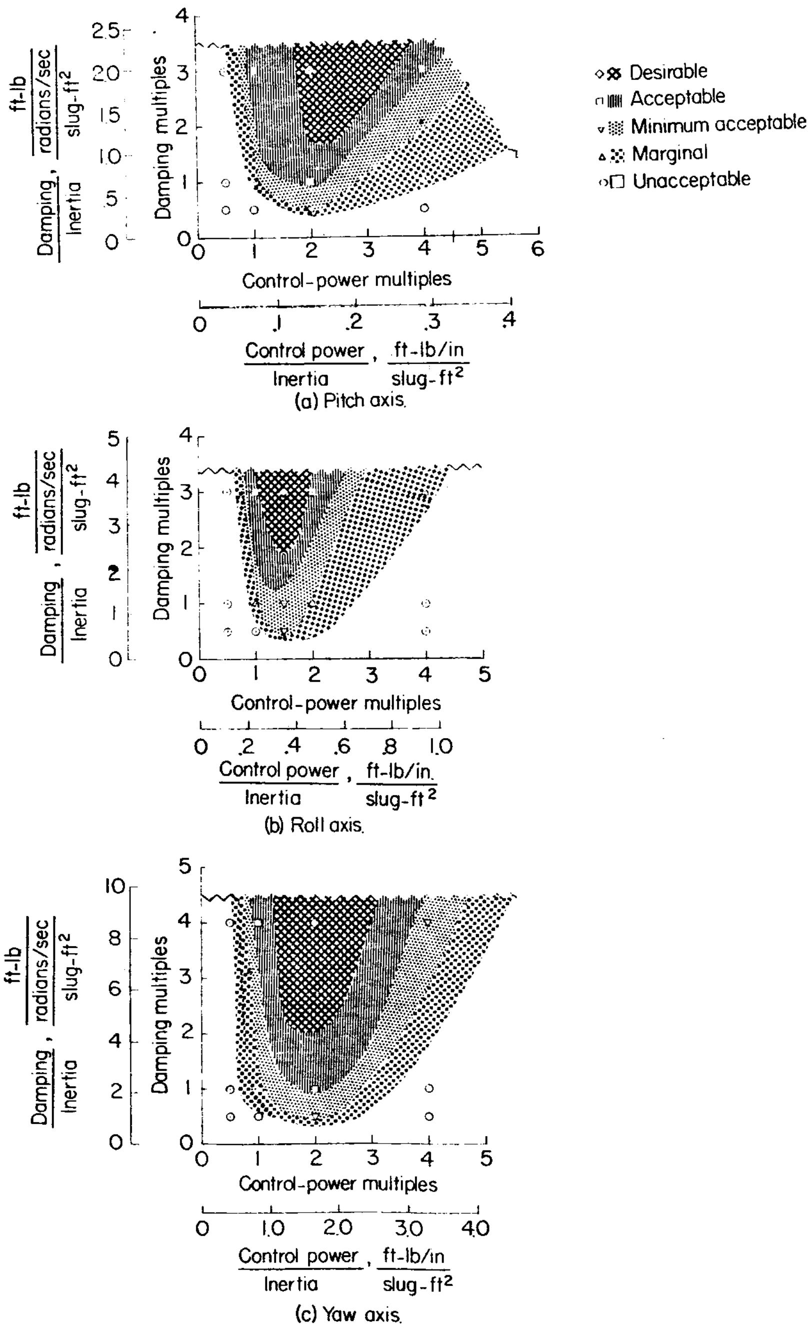
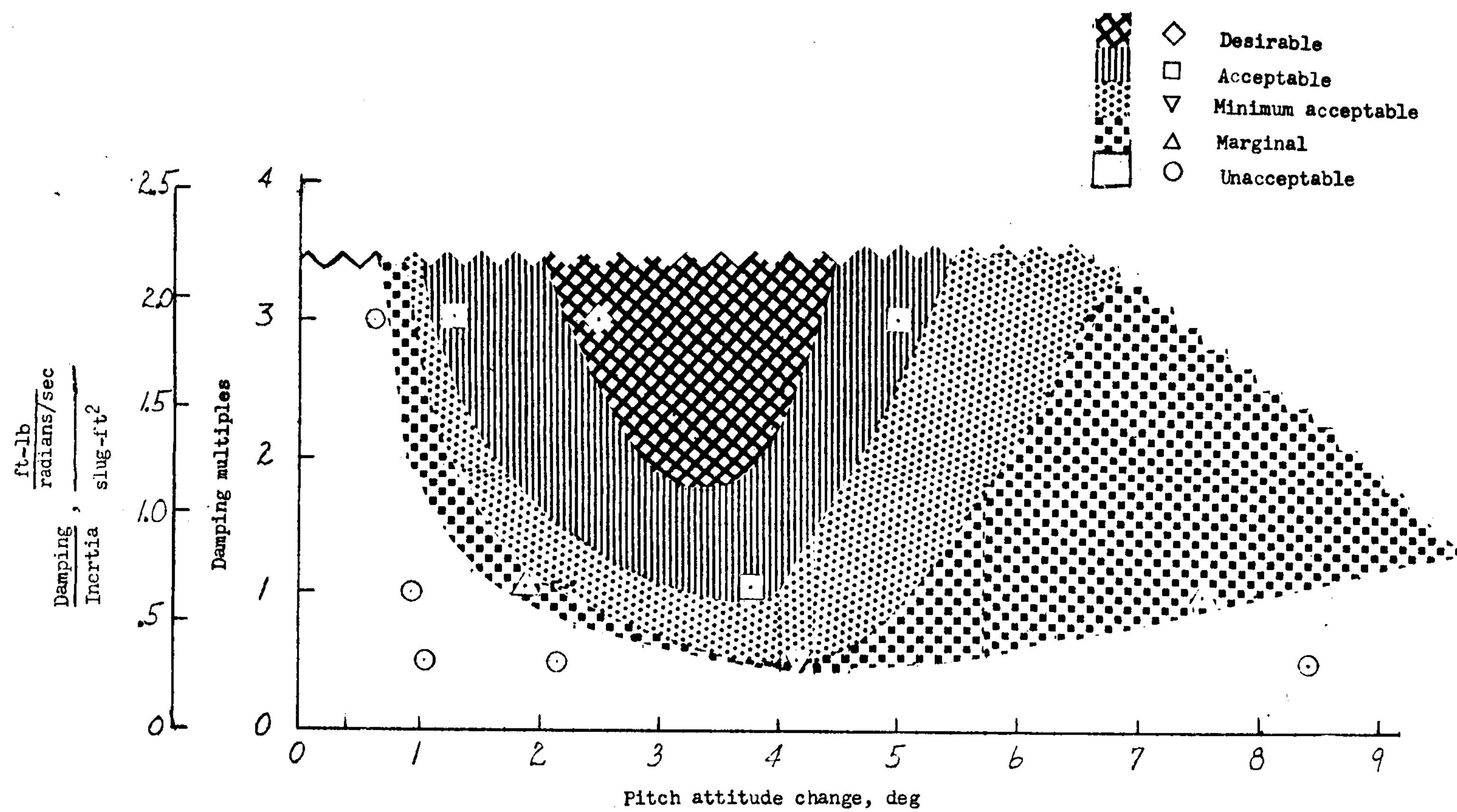
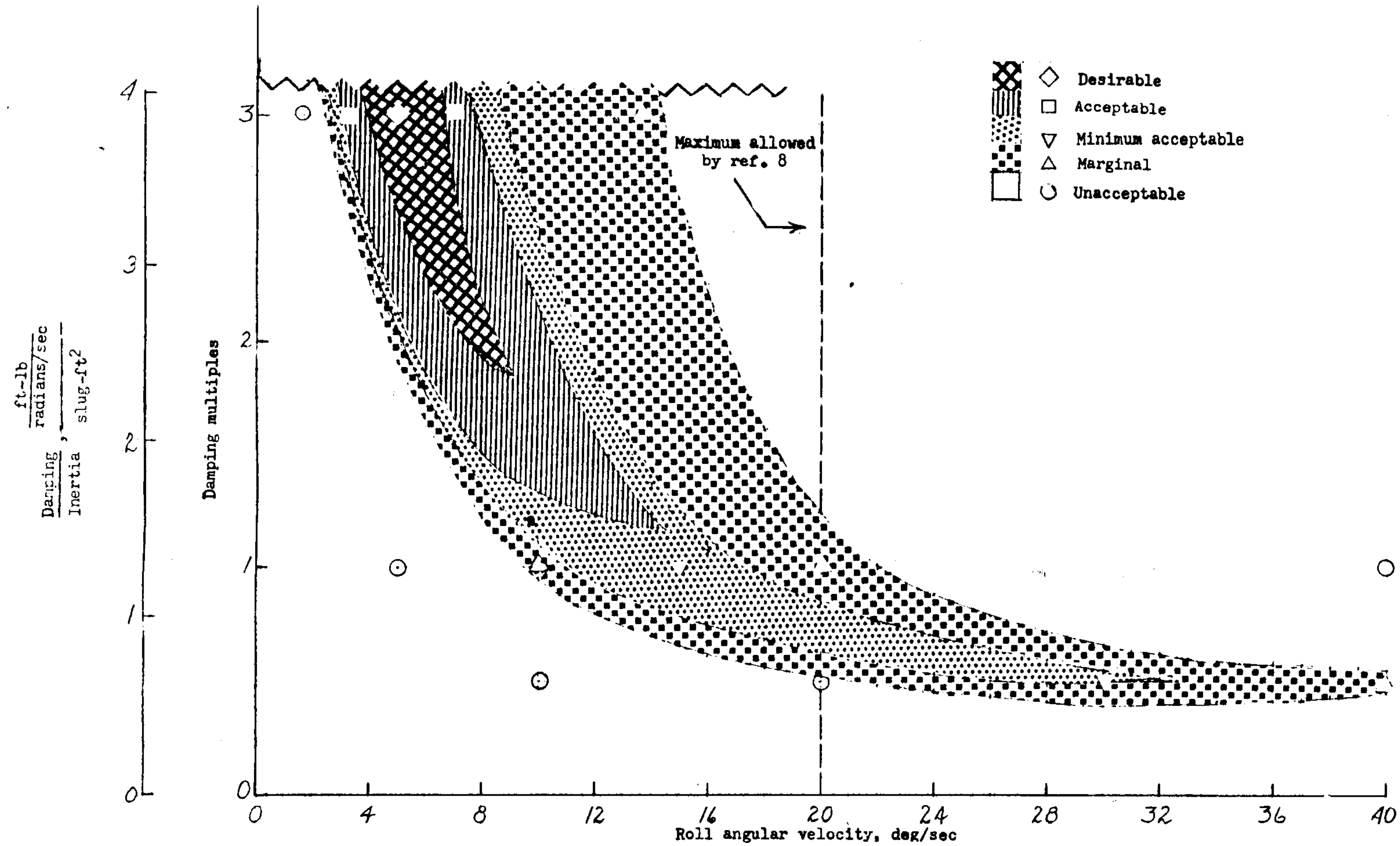


Figure 7.- Handling-qualities boundaries as a function of damping and control power.



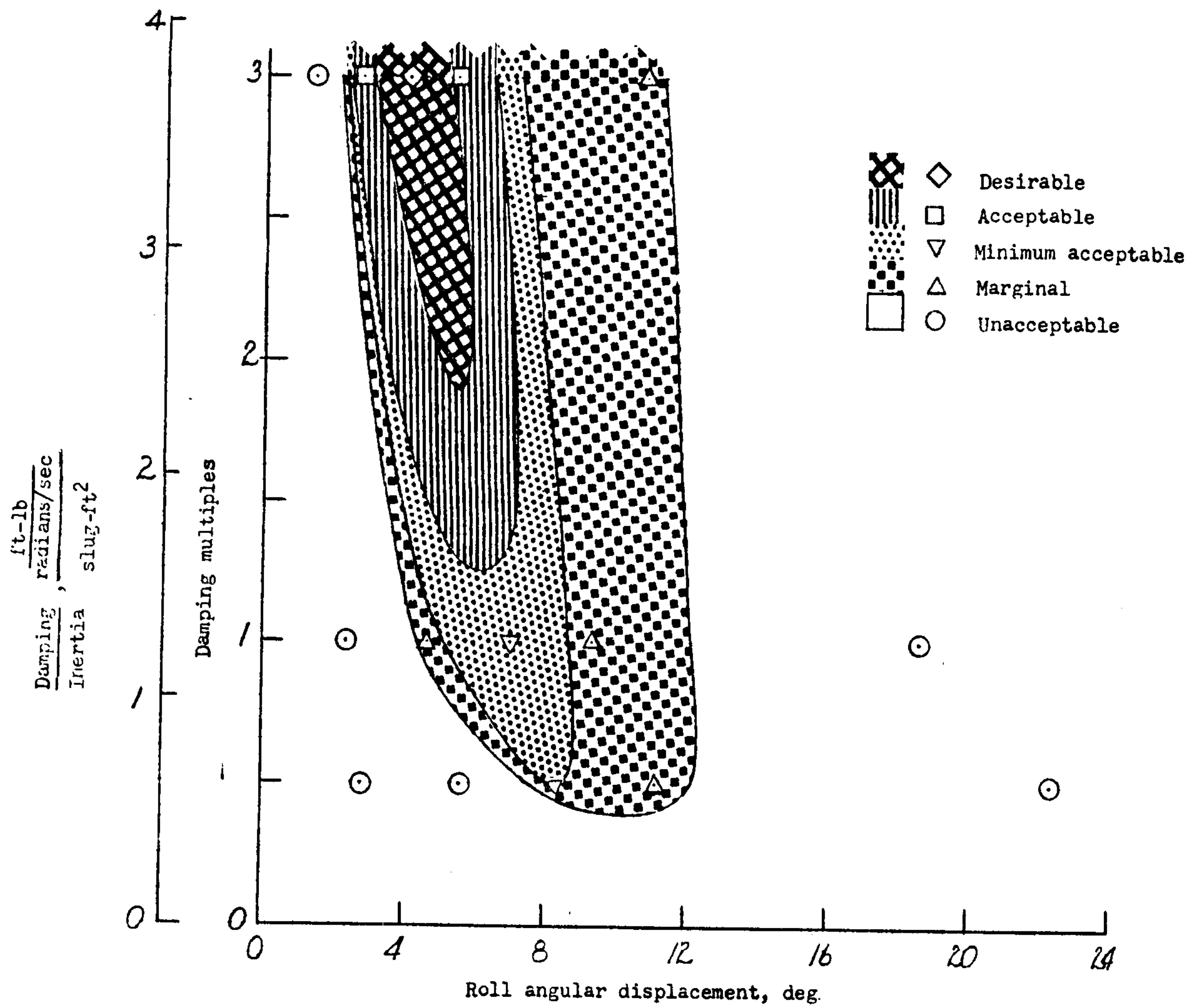
(a) Pitch attitude change after 1 second for 1 inch of longitudinal stick travel.

Figure 8.- Handling-qualities boundaries as a function of damping and response quantities.



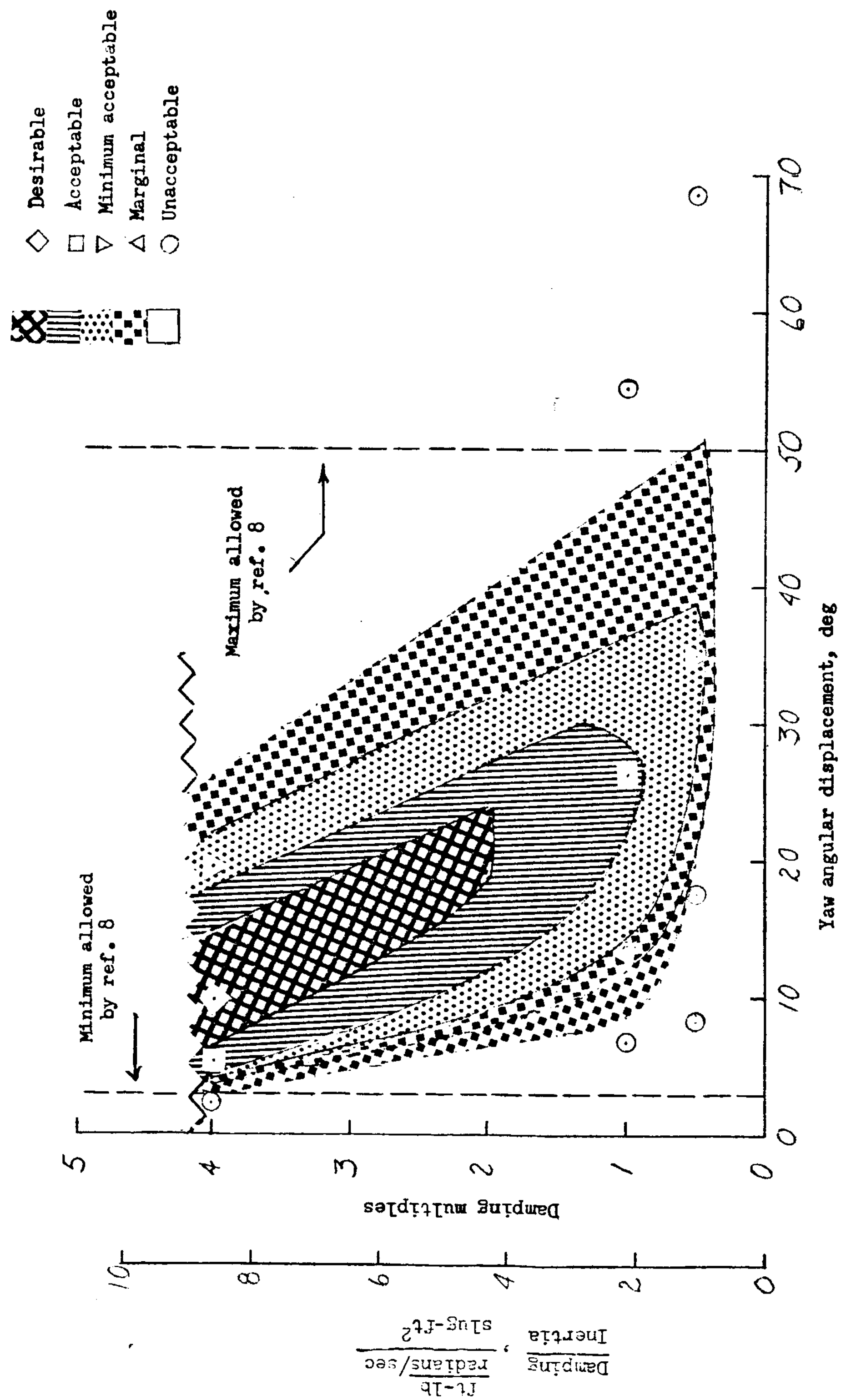
(b) Final roll velocity per inch of lateral cyclic stick travel.

Figure 8.- Continued.



(c) Roll angular displacement after 1 second for 1 inch of lateral stick travel.

Figure 8.- Continued.



(d) Yaw angular displacement after 1 second for 1 inch of pedal travel.

Figure 8.- Concluded.